Modeling Sediment Transport in Energetic Wave Bottom Boundary Layers

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LONG-TERM GOALS

The goals of this work are to develop better understanding of the sediment transport in wave bottom-boundary layers (WBBL) in the nearshore and inner shelf and to develop predictive capabilities for these effects as a function of important environmental parameters, such as wave heights, sediment properties, beach slope, local water depth, wave frequency spectra, and the presence of mean currents.

OBJECTIVES

The major tasks are to:
(1) implement the coupling of the sediment transport module into the existing 3-D turbulent boundary layer model.
(2) complete sets of direct numerical and large eddy simulations for two-phase flow (fluid-sediment suspensions) for sandy seabeds under uni-directional flow and energetic wave field conditions.
(3) determine proportions of sediment transport that occur in bed-load and suspended load within the model framework for different near-bed shear stresses.
(4) demonstrate quantitative model skill and range of application of parameterizations for two-phase coupling for different wave field conditions and sediment properties.
(5) compare the 3-D model results with our existing 1-D WBBL sediment transport model to evaluate the necessary parameterizations for turbulent transport of sediment and momentum through the water column.

APPROACH

We are extending current theory and numerical modeling capabilities for the wave bottom boundary layer to include the case of sediment transport over a sandy seabed for sheet flow conditions in the nearshore and inner shelf regions. The two-way coupling between the fluid and particulate phases is based on an Eulerian formulation. The fluid-sediment mixture has localized bulk properties (density, effective viscosity) functionally dependent upon the sediment concentration and a parameterizion of the particle-particle collisional frequency that dominates molecular diffusion of momentum in regions of large particle concentration similar to constitutive relations for a dense molecular gas as described by the kinetic theory of gases. The work involves theoretical development, numerical computations, and comparison with field and laboratory results.

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In our work, the key unknown is the approximate functional dependence of the diffusivities of the fluid and solid phases on the sediment concentration and local kinetic energy. In the porous sea-bed the volume fraction of loosely packed sediment is typically around 55%, while in the suspended load, with high sediment concentrations of 100 grams/liter, the volume fraction is typically less than 5%. The mobile sheet typically is only several grain diameters thick and has volume fractions, ν, between these values. Across this range the effective bulk viscosity of the mixture will vary strongly, representative of high particle-particle cohesion in the bed, to rare collisions in the suspended load.

The fundamental two-phase liquid-particulate theory for the bedload transport of coarse particles is given by Jenkins and Hanes (1998). The theory is one-dimensional and describes the two-component bottom boundary layer in detail. The basic approach is to formulate momentum and energy conservation equations for both the fluid and the particles. For example, the momentum conservation equations for the fluid and the particles, respectively, can be written in terms of the density, velocity, and stress tensors:

$$\rho_f(1-\nu)\left[\frac{\partial \boldsymbol{v}_f}{\partial t}+\left(\boldsymbol{v}_f\cdot\nabla\right)\boldsymbol{v}_f\right]=-(1-\nu)\nabla p_f+\nabla\cdot\boldsymbol{T}_f^*+\rho_f(1-\nu)\boldsymbol{g}-D(\boldsymbol{V}_f-\boldsymbol{v}_s) \qquad (1)$$

$$\rho_s\nu\left[\frac{\partial \boldsymbol{V}_s}{\partial t}+\left(\boldsymbol{V}_s\cdot\nabla\right)\boldsymbol{V}_s\right]=-\nabla\left(\nu p_s\right)+\nabla\cdot\boldsymbol{T}_s^*+\rho_s\nu\boldsymbol{g}+p_f\nabla\nu+D(\boldsymbol{V}_f-\boldsymbol{v}_s) \qquad (2)$$

The last term in each equation represents the effect of fluid-particle drag on the balance of momentum for each component, where the term D represents a drag coefficient that depends upon both the concentration of the solid particles and the particle Reynolds number. The kinetic theory is employed to describe the stress tensor of the granular phase, e.g., $T_{s,ij}=\alpha E\frac{\partial v_{s,i}}{\partial x_j}$, where $\alpha=\frac{8d_{50}\rho_s\nu G T^{1/2}}{5\pi^{1/2}}$, $E\equiv 1+\frac{\pi}{12}\left(1+\frac{5}{8G}\right)^2$, and $G\equiv\nu\frac{2-\nu}{2(1-\nu)^3}$ is the concentration dependence of the radial distribution for colliding particles (Carnahan and Starling, 1979), and 3T is the mean square of the particle velocity fluctuations (Chapman and Cowling, 1970). The equations are closed through the use of energy conservations equations for each phase.

This theory can be extended to describe the transport of sand by waves and currents under sheet flow (flat bed) conditions. The physical processes that need to be incorporated into the theory are the effects of fluid turbulence on the suspension of sediment, the effect of the interstitial water upon grain-to-grain collisions, and the momentum and energy interactions due to the fluctuations in the grain and fluid velocities in unsteady, reversing flow. The existing one-dimensional theory describes the flow of particles driven by the mean velocity difference between the fluid and the particles. Although the fluid is assumed turbulent, the effect of the turbulence on the particle scale motions is not modeled. Thus, the theory lacks turbulent suspension, an important process influencing sand transport in the nearshore zone. The approach to adding turbulent suspension in the one-dimensional model will be to modify the vertical momentum equation to include the force that results from correlated fluctuations in the particle concentration and vertical velocity (<w'C'>). These will be estimated from the three-dimensional simulations and included in the one-dimensional model using a mixing length closure, similar to the modeling of the horizontal fluid momentum equation. These three-dimensional simulations adopt the Eulerian approach for a dense flow of particles, considering the mixture to

behave as a continuum and solving conservation equations for the average properties of the particles in the flow. In our approach, Equations (1) and (2), the continuity equation, and energy conservation equations are solved in a three-dimensional control volume. The approximate dimensions of the model domain are 10 cm on each side (i.e., 1000 cm^3). We invoke periodicity at the lateral boundaries, employ an open boundary at the upper boundary with a specified oscillatory free stream flow, $U_\infty(t)$, and include a movable sediment layer (approximately 1-2 cm thick) representing the sea bed in the bottom portion of the domain for which over the most part $\rho_s > \rho_f$ and $v_s \approx v_f \approx 0$. In our previous simulations of the wave bottom boundary layer (WBBL) the DNS model typically utilizes vertical grid resolution of approximately 0.1 mm in the strong shear layer near the sea bed. This appears also to be sufficient for simulations of dynamic sheet flow layers which are typically on the order of 10 grain diameters thick (i.e., 1-5 mm). Thus, the sheet flow layer and suspended sediment concentration profiles will evolve naturally through the course of the wave cycle as described by the coupled, time-dependent, two-phase mixture equations.

The two phases are strongly coupled, through direct momentum exchange between the fluid and particles caused by drag and pressure gradients, through stratification and gravitational settling effects, and through spatial variation of the effective kinematic viscosity associated with regions of high particle densities and localized regions of elevated kinetic energy that increase the frequency and strength of particle collisions, as contemplated by the kinetic theory. An important bulk parameterization in the three-dimensional model is the temporal-spatial dependence of the stress tensor in regions of significant sediment loading.

The collision between two particles is typically characterized by the total loss of energy, which is parameterized by the coefficient of restitution. The presence of water as the interstitial fluid can have a significant influence upon the effective coefficient of restitution. However, the effect of the water upon collisions of sand sized particles is relatively unknown. A challenging aspect of this model development involves the interactions between fluid turbulence and fluctuating grain velocities. Such interactions may either increase or decrease the fluid turbulence depending upon the relative intensities of the fluid and particle momentum fluctuations. Under steady flow conditions, such interactions may not be significant, but under unsteady, reversing flows, it is essential to include them. This is because these interactions influence the basic balance between the production and dissipation of fluid turbulence, and provide the key to maintenance of the suspended sediment during times of flow reversal with zero mean velocity.

WORK COMPLETED

During this phase of the project our focus has been on model development, coding, testing and debugging. We are modifying our variable density turbulent boundary layer model (Cook and Dimotakis, 2001) to accommodate the spatially varying mass and momentum diffusion coefficients following the approach of Jenkins and Hanes (1998) outlined above.

RESULTS

In the first phase of the model development we are studying the effects of variable density and variable viscosity in the response of the wave boundary layer. Figure 1 shows the simulated boundary layer during a phase of turbulence that occurs near flow reversal in the oscillatory flow.

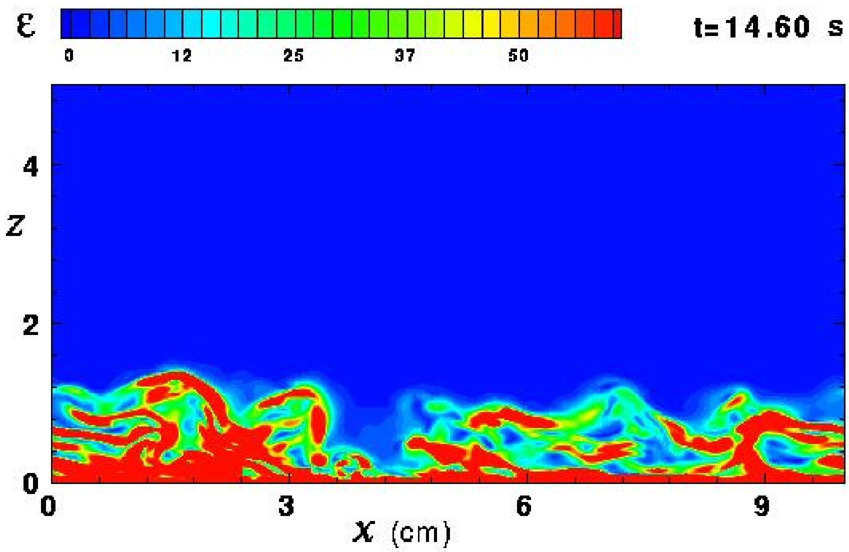

Figure 1: Dissipation rate contours in the boundary layer over an immobile bed during mixing.

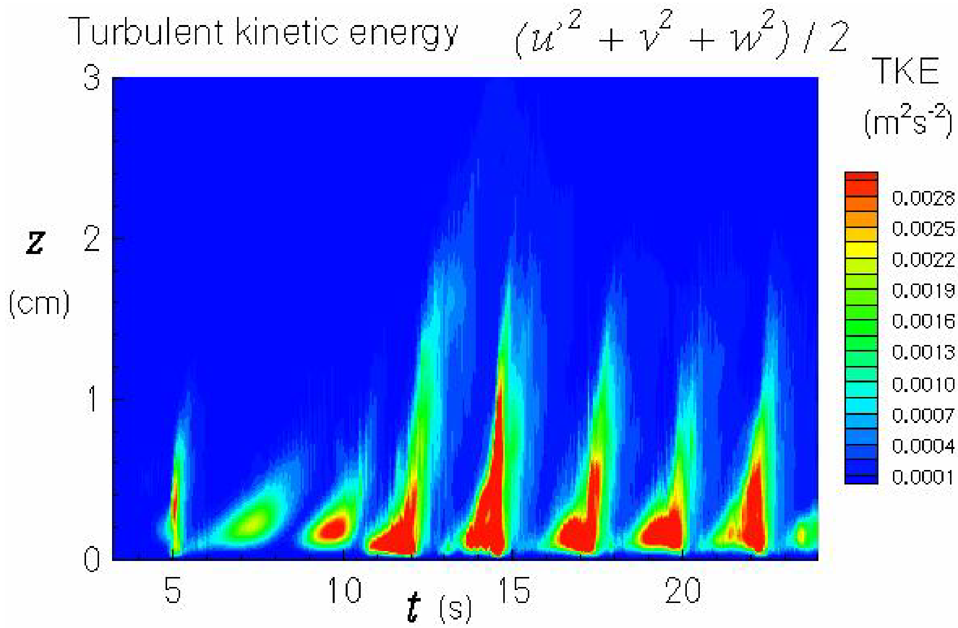

Figure 2: Turbulent kinetic energy as a function of time shows the episodic nature of turbulence in the wave bottom boundary layer for a 5 second free stream oscillation.

The horizontally averaged turbulent kinetic energy (TKE) in the boundary layer, as a function of height, *z*, and time, *t*, for the forcing conditions illustrated in Figure 1 are shown in Figure 2. In general, a quasi-steady flow response to periodic wave forcing is achieved. Then, turbulent bursts become episodic in nature, occuring approximately twice per wave period (*i.e.*, here every 2.5 s). The decay of turbulence is more sudden than the onset. It has been found that the magnitude of the acceleration and deceleration are important parameters in controlling the turbulence levels in the boundary layer. When the acceleration is strong, turbulent production is inhibited. Results show that as the wave amplitude, U_m, decreases (*i.e.*, Reynolds number decreases), the turbulent kinetic energy decreases, with transitional Reynolds numbers in the numerical simulations very similar to those

observed in laboratory experiments of Jonsson (1966). The numerical experiments indicate that as the wave period increases the flow becomes more turbulent and the turbulent boundary layer

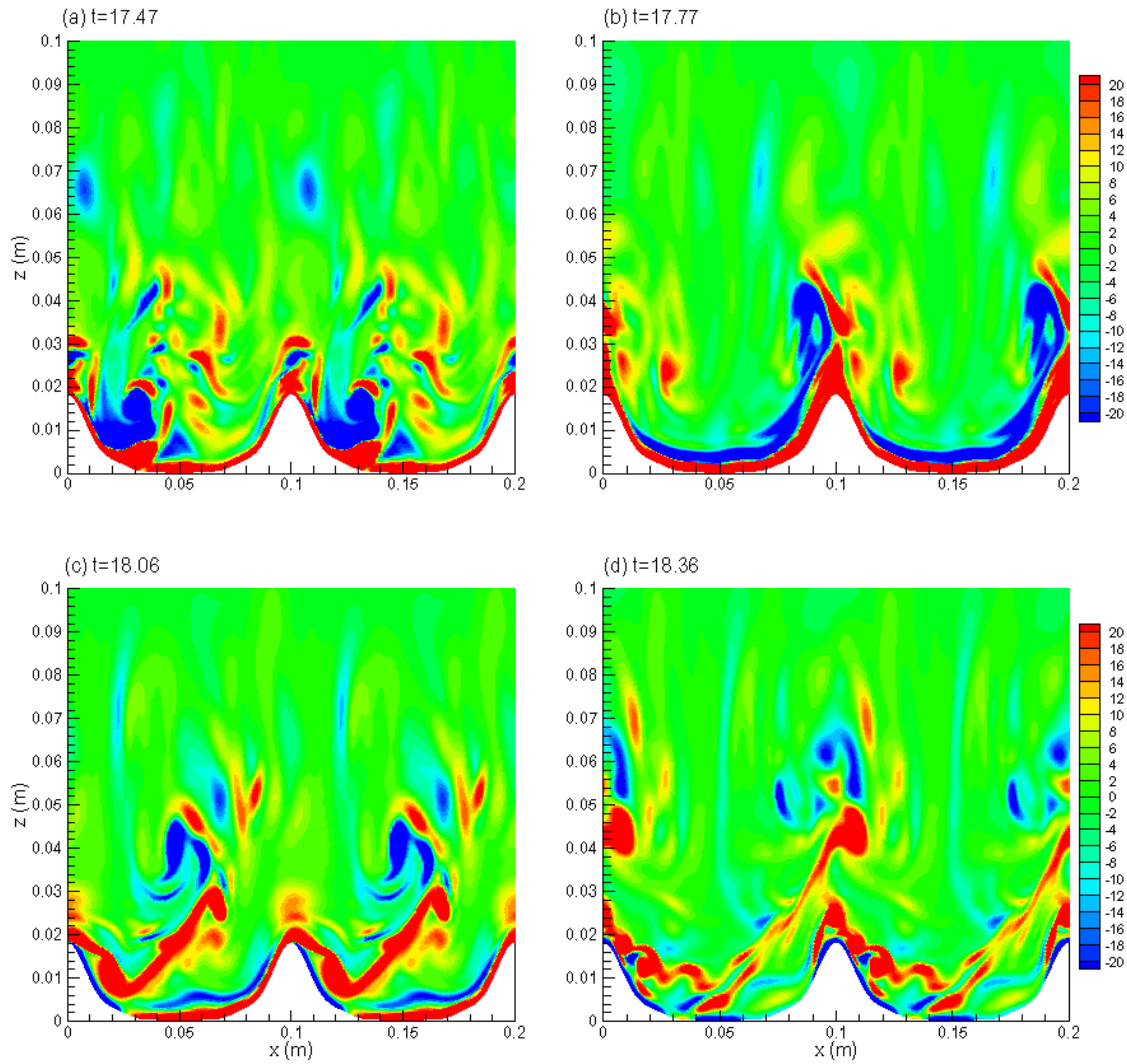

Figure 3: LES of oscillatory flow with period 2.45 seconds over a steep crested sand ripple using the variable viscosity boundary layer model.

thickness increases. In contrast with oscillatory flow over a flat bottom boundary the WBBL over a "sand" ripple appears significantly more turbulent throughout the full flow period. Figure 3 shows velocity vectors and vorticity fields in a vertical cross section of the flow for an experiment over a sand ripple that is 10 cm long and 1.8 cm tall with a wave period of 2.45 s and a maximum wave orbital velocity of 20 cm/s. The experiment is a duplication of lab experiments by Ransoma and Sleath (1994) that produced sand ripples of these dimensions as sediment is deposited at each node of the wave orbital excursion. Turbulent bursts still occur most strongly at phases of flow reversal. The bursts originating during flow reversal, however, are not damped out during flow acceleration, but remain strong throughout the wave period. An observed mechanism is the production of turbulence in the

boundary layer by separation over ripple crests during periods of strong onshore and offshore flow that was necessarily absent with flows over smooth boundaries.

IMPACT/APPLICATIONS

Improved understanding of the near shore environment has potential benefits for society in several areas. These include shore protection against beach erosion, understanding the behavior of shoaling waves, keeping waterways open for shipping in harbors, ports and inlets, safety for recreational beach users (e.g., from dangerous rip currents) and in defense of the nation when activities encompass littoral regions. We will have a strong indication that we understand and can quantify important nearshore processes when predictive models can match field observations. For the scientific community, this is still a work in progress.

TRANSITIONS

Our major transition has been to include variable density effects in the fluid-sediment mixture in the wave bottom boundary layer.

RELATED PROJECTS

1. Tim Stanton at the Naval Post Graduate School is using our model for comparison with some of his recent field measurements of the WBBL from the SHOWEX field experiment.

2. A group of near shore researchers, led by Jim Kirby at the University of Delaware, and including Daniel Hanes of the University of Florida, focusing on sediment transport properties, are developing related near shore community models under a NOPP project.

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